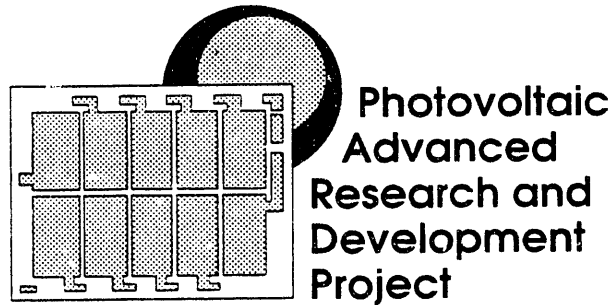


NREL/CP-413-4845
DE92001243

MAY 18 1992



NREL PV AR&D 11th Review Meeting

May 13-15, 1992

Denver, Colorado

Abstracts

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ABSTRACTS

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On September 16, 1991 the Solar Energy Institute was designated a national laboratory, and its name was changed to the National Renewable Energy Laboratory.

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Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A07

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications which are generally available in most libraries: *Energy Research Abstracts (ERA)*; *Government Reports Announcements and Index (GRA and I)*; *Scientific and Technical Abstract Reports (STAR)*; and publication NTIS-PR-360 available from NTIS at the above address.

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SESSION I

WEDNESDAY A.M.

**PV MANUFACTURING
AND MODULE DEVELOPMENT**

THE PHOTOVOLTAIC MANUFACTURING TECHNOLOGY PROJECT

C.E. Witt, R.L. Mitchell, and G.D. Mooney

National Renewable Energy Laboratory

The Photovoltaic Manufacturing Technology (PVMaT) project is a historic government/industry photovoltaic manufacturing R&D partnership composed of joint efforts between the federal government (through the U.S. Department of Energy) and members of the U.S. photovoltaic (PV) industry. Initiated early in 1990, it is designed to assist the U.S. PV industry in improving manufacturing processes, accelerating manufacturing cost reductions for PV modules, increasing commercial product performance, and generally laying the groundwork for a substantial scaleup of U.S.-based PV manufacturing plant capabilities.

Phase 1 of this program, the problem identification phase, was completed early in 1991. Phase 1 competitive bidding was open to any U.S. firm with existing PV manufacturing capabilities, regardless of material or module design. Twenty-two contracts of up to \$50,000 each were awarded. Phase 2 is the process-specific solution phase of the project and addresses problems of specific manufacturers. Phase 2A, which is now under way, was open only to Phase 1 participants. Each of the subcontracts is of up to three years duration and is highly cost-shared between the U.S. government and U.S. industrial participants. A second, overlapping, and similar process-specific solicitation, (Phase 2B) is planned to follow soon and will be open to all U.S. PV manufacturing companies. A third portion of the program, called Phase 3, is also under way, though slightly behind Phase 2. In Phase 3, because of the general interest to industry, some general issues related to PV module development will be studied through various teaming arrangements. The PVMaT project's ultimate goal is to ensure that U.S. industry retains and extends its world leadership role in the manufacture and commercial development of PV components and systems. The activities to date have received outstanding support, and the level of interest in participation is exceptional for this program.

BUILDING OPPORTUNITIES IN THE U.S. FOR PHOTOVOLTAICS -- PV:BONUS

R.W. Taylor

National Renewable Energy Laboratory

The PV:BONUS program is an infrastructure and product development program. The objective is to develop a U.S. PV-buildings industry based on the delivery of reliable, cost-effective PV products by PV and building equipment suppliers to informed, participating builders for use in residential, commercial and institutional buildings. The ultimate goal is commercially viable products and market niche demonstrations that lead to manufacturer commitments to pursue production and sales. The three phases of the initiative are (1) concept development, (2) product development and testing, and (3) field demonstration and performance verification. The program will be supported by technology validation (testing) activities at NREL and a cooperative government/industry education and training program.

GaAs CONCENTRATOR CELL PRODUCTION COST ANALYSIS

S. Hogan, M. Nowlan, and S. Wojtczuk

Spire Corporation

The utilization of GaAs in photovoltaic applications has been hindered by the cost of substrates and processing. This presentation examines the cost effectiveness of GaAs cells for use in photovoltaic modules when produced at the 50 MW level per year. Information on costs associated with substrates, epitaxial processing, and subsequent device fabrication will be compared to allowable costs as projected by the US DOE.

The high cost of GaAs solar cells can be mitigated by use of low cost substrates or high-concentration applications. These costs can be accommodated when the production level is sufficiently high to take advantage of economies of scale in device processing and substrate price benefits when procured at high volumes. We have found that development of processing equipment, both for epitaxial growth and device processing, is the key to obtaining production costs consistent with DOE goals. Successfully achieving these cost goals for GaAs technology is likely.

**RECENT PROGRESS IN HIGH-EFFICIENCY, LARGE AREA
CuInSe₂-BASED THIN FILM MODULES***

K.W. Mitchell, R.R. Gay, C.V. Fredric, and C. Eberspacher
Siemens Solar Industries

Siemens Solar Industries began this 3-year, 3-phase cost shared contract on May 1, 1991 with the overall goal of demonstrating 12.5% aperture efficient, large-area (0.4 m²) encapsulated thin film CuInSe₂ (CIS) modules. The best encapsulated large-area CIS module power output prior to this contract was 33.7 W, 8.7% aperture efficiency (verified by NREL) over a 0.388 m² aperture area.

Work to date has focused on characterizing and controlling macroscopic electrical shunts caused by microscopic defects in the substrates, the CIS films, and in all of the thin film components in the areas adjacent to the module patterns.

To date, the best encapsulated large-area CIS module verified by NREL was 37.7 W, 9.7% aperture efficiency over an 0.388 m² aperture area

* This work supported by the U.S. Department of Energy under Contract No. ZN-1-19019-5.

STATUS OF CdTe/CdS DEVELOPMENT AT PHOTON ENERGY, INC.

S.P. Albright, B. Ackerman, R.R. Chamberlin, and J.F. Jordan
Photon Energy, Inc.

The status of development of CdTe/CdS devices and modules at Photon Energy, Inc. (PEI) includes attaining milestones such as:

- Efficiencies of 12.7% have been achieved on small area devices.
- Modules with areas of 929 cm² have achieved over 8% aperture area efficiency (active area up to approximately 10%).
- Modules with areas of 3716 cm² have been tested at NREL at 23.1 watts (21.3 watts, normalized via a pyranometer).
- Life testing at NREL (and PEI) shows no inherent stability problems within the measurement error.

PROGRESS TOWARD STABLE AMORPHOUS SILICON PHOTOVOLTAIC MODULES

F.J. Kampas, J. Xi, J. del Cueto, and R. Romero

Advanced Photovoltaic Systems

Amorphous silicon photovoltaic modules are subject to several degradation mechanisms which must be addressed in order to produce a reliable module. The Staebler-Wronski effect is particular to amorphous silicon. Interdiffusion between layers and electrochemical corrosion are generic to thin-film photovoltaics. Finally, there are the usual problems associated with long-term outdoor exposure. This talk will survey APS' results on these problems. The topics covered will include high quality i-layers which do not exhibit the Staebler-Wronski effect, laboratory results for 1 square foot tandem modules, and test and field performance results for 12½ square foot single-junction modules.

NOTES

NOTES

SESSION I

WEDNESDAY P.M.

**PV MANUFACTURING
AND MODULE DEVELOPMENT
(continued)**

**HIGH EFFICIENCY CONCENTRATOR MODULES
USING SINGLE AND MULTI-JUNCTION III-V SOLAR CELLS**

M. S. Kuryla

High Technology Center

Boeing Defense & Space Group

Solar cells fabricated from various III-V compounds have produced laboratory conversion efficiencies approaching 29% for single junction structures and 35% for multijunction structures under concentrated illumination. Due to their relatively limited availability, few of these devices have been incorporated into actual concentrator module structures.

Details are presented from two development efforts which have incorporated III-V cells into high efficiency prototype concentrator modules: Varian's GaAs module operating at a geometric concentration ratio of 950 suns with flat fresnel lenses; and Boeing's tandem GaAs/GaSb module operating at 50 suns with Intech's domed fresnel lenses.

DESIGN CRITERIA OF THE SPHERAL SOLAR CELL

J.D. Levine

Texas Instruments

Design criteria were used to generate a systems approach to a large scale PV product, based on silicon. Feedstock of metallurgical-grade-silicon is shown to be adequate for PV markets far exceeding 1,000 MW/year, without requiring the limited quantity of semiconductor-grade-silicon rejects commonly used in the PV industry. The sphere-foil cell structure eliminates active area loss due to metallization patterns and conducting straps. Optics calculations show the benefit of multiple scattering. Sphere inclusions are rare but expected with inexpensive feedstock. A generalized equation is derived showing the cell voltage degradation caused by spheres with low Voc's, prior to their isolation by the selective electrodis-solution process.

**DEVELOPMENT OF MONOLITHICALLY INTEGRATED
SILICON-FILM MODULES**

J.A. Rand, J.E. Cotter, T.H. Lampros, A.E. Ingram,
T.R. Ruffins, R.B. Hall, and A.M. Barnett
AstroPower, Inc.

Silicon-Film Product III is being developed as a low cost, stable device for large scale terrestrial power applications. The Product III structure is a thin ($<100 \mu\text{m}$) polycrystalline silicon layer on a non-conductive supporting ceramic substrate. The presence of the substrate allows cells to be isolated and interconnected monolithically. The long term goal for the product is efficiencies over 18% on areas greater than 1200 cm^2 . The high efficiency will be based on thin polycrystalline silicon that incorporates light trapping and a passivated back surface. Short term goals are focused on the development of large area ceramics, a monolithic interconnection process, and fabricating 100 cm^2 solar cells. A V_{oc} of 12.1 V has been demonstrated on a 22 element monolithically interconnected string fabricated with single crystal test structures.

PROGRESS TOWARDS HIGH PERFORMANCE LOW COST

a-Si:H ALLOY MULTIJUNCTION ALLOYS

A. Catalano, M. Bennett, J. Newton, L. Yang, Y.-M. Li,

B. Fiesemann, S. Wiedeman, and R.V. D'Aiello

Thin Film Division

Solarex Corporation

a-Si:H alloy based multijunction, multibandgap solar cells remain one of the best alternatives for obtaining high stabilized conversion efficiencies while maintaining the low cost implicit in the amorphous silicon thin film approach. Efforts to develop stabilized module efficiencies over 12% have led to numerous important advances:

- An 10.85% module efficiency has been demonstrated using a thin, 4000Å middle junction structure and 1.5 eV a-SiGe:H lower junction.
- An accurate model of the light-induced degradation has been developed. Among its important conclusions we find that degradation is self-limiting, and this is confirmed by experiment.
- a-SiC:H devices have been prepared using novel feedstocks. These devices have a stability comparable to a-Si:H but have achieved open circuit voltage of close to 1 Volt with good fill factor.
- Atmospheric CVD of ZnO has yielded films whose transmission and conductivity are superior to tin oxide. Devices prepared on the films exhibit a 14% increase in short circuit current. Thin triple junction devices over 11% have been prepared on ZnO.

**ADVANCES IN AMORPHOUS SILICON ALLOY-BASED
MULTIJUNCTION CELLS AND MODULES**

S. Guha, J. Yang, A. Banerjee, T. Glatfelter, and X. Xu
United Solar Systems Corp.

Multijunction amorphous silicon alloy-based solar cells and modules offer the potential of obtaining high efficiency with long-term stability against light-induced degradation. We have studied the stability of the component cells of the multijunction devices prepared under different deposition conditions. We observe a definite correlation between the microstructure of the intrinsic materials and initial and light-degraded performance of the cells. Using suitable deposition conditions and optimum matching of the component cells, we have fabricated double-junction dual-bandgap cells which show stabilized active-area efficiency of 11% after 600 hours of one-sun illumination at 50°C. Double-junction and triple-junction modules of 900 cm² area have been fabricated, and the performance of these panels will be discussed.

NOTES

SESSION II

WEDNESDAY P.M.

PV MATERIALS AND DEVICES

**CHARACTERIZATION OF PHOTOVOLTAIC TECHNOLOGIES:
FROM ARRAYS TO ATOMS**

L.L. Kazmerski

National Renewable Energy Laboratory

The advancement of photovoltaic technologies is closely linked with the characterization, measurement and testing of the various components involved. Over the past 14 years, the NREL(SERI) laboratories have collaborated with the U.S. Photovoltaic industry, university and government research laboratories in the identification and solution of problems, documentation of performance results, determination of effects of processing changes, and development of standard measurement techniques for cell and module technologies. This paper summarizes the range of support characterization available to the U.S. Photovoltaic Program, with specific examples of recent contributions to single crystal, polycrystalline and amorphous technologies. These include critical determinations of cell and module performance parameters under standard conditions, contributions to component reliability/durability issues, collaboration in establishing optimum processing parameters, and development of photovoltaic-specific measurement techniques. Some emphasis is given to the frontiers of characterization technologies, and their possible application to photovoltaics. Among these are those involved with nanoscale science and technology, providing the capability to link atomic level events (imaging, nanocharacterization and manipulation of single atoms) with the understanding and possible atomic engineering of photovoltaic semiconductors.

GROWTH AND PROPERTIES OF THIN CRYSTALLINE SILICON LAYERS

T.F. Ciszek, R.W. Burrows, T.H. Wang, and J. Alleman
National Renewable Energy Laboratory

In this presentation, we will discuss recent in-house work at NREL related to thin-layer crystalline silicon for PV use. With suitable light trapping and back surface reflection designs, it may be possible to substantially reduce the physical thickness of silicon solar cells while still maintaining an optical path length near 100 μm . Thus, there is current interest in thin-layer (10-50 μm) silicon for PV applications. We have used high-temperature ($\sim 1000^\circ\text{C}$) metal solution growth to form thin silicon layers on single-crystal silicon substrates for the purpose of studying variations in growth properties and characteristics of the thin Si layers. Growth conditions, morphology, solvent incorporation characteristics, and electrical properties of the solution-grown layers will be presented and discussed.

We wish to experimentally determine relationships between grain size, thickness, and cell performance in thin-layer silicon. As a prelude to that study, we have developed methods to produce high-purity (float-zoned) ingots with grain size that increases by more than an order of magnitude from seed to tail of the ingot. This is accomplished by using a fine-grained, large-area seed to initiate growth. We also developed procedures to double-side polish wafers from this material to thicknesses as small as 40 μm . Cell fabrication on wafers less than 100 μm thick has been achieved. In subsequent work, we will generate a matrix of grain sizes and thicknesses upon which to determine performance parameter variations.

**PROPERTIES OF HYDROGENATED AMORPHOUS SILICON
PRODUCED AT HIGH TEMPERATURE**

R.S. Crandall, A.H. Mahan, and B.Nelson
National Renewable Energy Laboratory

A comprehensive study of hydrogenated amorphous silicon (a-Si:H) deposited by hot wire and conventional glow discharge suggests that temperatures above the so called optimum 250C° substrate temperature can produce device quality films. These films show enhanced transport properties and improved structural order. In addition we show that material can be produced with just enough hydrogen to passivate most of the dangling bonds present in unhydrogenated a-Si:H.

HIGH EFFICIENCY THIN FILM CADMIUM TELLURIDE SOLAR CELLS

T.L. Chu*, S.S. Chu*, J. Britt, G. Chen,
C. Ferekides, N. Schultz, C. Wang, and C.Q. Wu
University of South Florida

Cadmium sulfide (CdS), grown from an aqueous solution, and zinc oxide (ZnO), cadmium zinc sulfide ($\text{Cd}_{1-x}\text{Zn}_x\text{S}$) and zinc selenide (ZnSe) deposited by metalorganic chemical vapor deposition (MOCVD) have been used as the window for thin film cadmium telluride (CdTe) solar cells. Thin film solar cells were prepared by the successive deposition of the window and p-CdTe (by MOCVD and close-spaced sublimation, CSS) on $\text{SnO}_2\text{:F}$ /glass substrates. CdS/CdTe(CSS) solar cells show considerably better characteristics than CdS/CdTe(MOCVD) solar cells because of the better microstructure of CSS CdTe films. Total area conversion efficiency of 14.6%, verified by the National Renewable Energy Laboratory, has been achieved for solar cells of about 1 cm^2 area. Solar cells prepared with ZnO, ZnSe, and $\text{Cd}_{1-x}\text{Zn}_x\text{S}$ as windows have a significantly lower photovoltage than CdS/CdTe solar cells.

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PROGRESS IN CAST POLYCRYSTALLINE SILICON

J.H. Wohlgemuth
Solarex Corporation

Cast polycrystalline silicon is used as the substrate for a large fraction of the commercial PV modules sold today. There have been significant improvements in the efficiency of the cells used in these modules, going from 8 to 9% in the early 1980's to 13 to 14% today. Laboratory cells with efficiencies as high as 17.8% have been achieved on polycrystalline substrates at the University of New South Wales. These higher efficiencies have been as a result of improved material quality and uniformity as well as due to post growth treatments such as passivation, with hydrogen alone or as part of plasma CVD deposition of silicon nitride antireflective coating, and gettering with phosphorous and aluminum. The result of this work has been realization that except for the inability to be texture etched, cast polycrystalline silicon substrates can produce cells with efficiencies equivalent to single crystal CZ silicon.

NOTES

SESSION II

THURSDAY A.M.

**PV MATERIALS AND DEVICES
(continued)**

CHARACTERIZATION OF SILICON SOLAR CELL SUBSTRATES

B.L. Sopori

National Renewable Energy Laboratory

Solar cell substrates are known to contain material non-uniformities arising from crystal defects, impurity inhomogeneities and residual stresses. These non-uniformities, along with those introduced during solar cell processing, are finally manifested as the areal variations in the solar cell performance. In a large-area cell, the low-performing regions can act as "sinks" to dissipate power internally, thus reducing the cell output. A very useful approach to fully characterize the nature of such nonuniformities is to fabricate small-area mesa diode arrays on the substrates, which can be probed to determine the spatial variations in the cell and the material parameters. However, small-area devices are often accompanied by large leakage currents, making it difficult to collect meaningful results. We will describe a fabrication process that produces edge-passivated devices of extremely low leakage currents. The devices can be automatically probed to produce spatial maps of resistivity, V_{oc} , J_{sc} , FF, and the dark cell parameters. These parameters can be correlated with the local defect structure in the vicinity of each device. This technique allows one to separate the influence of the crystal defects and the impurities. These devices can also be used for measurements such as the minority carrier diffusion length or lifetime, and for DLTS. The information acquired via this technique can be related to improve material growth, design optimum cell fabrication processes and predict the large-area cell performance intrinsically controlled by the substrate.

NUMERICAL MODELING OF POLYCRYSTALLINE THIN FILM SOLAR CELLS

R.J. Schwartz, J.L. Gray, and Y.J. Lee

School of Electrical Engineering

Purdue University

This paper describes a numerical simulation code for the simulation of polycrystalline thin film solar cells, particularly CIS and CdTe based cells. ADEPT, A Device Emulation Program and Toolbox, is a general numerical simulation tool developed at Purdue and has been customized for the simulation of polycrystalline thin film solar cells. ADEPT is capable of running on IBM-compatible personal computers, permitting routine use as an analysis and design tool. Material models, code verification, device analysis, and device design issues will also be discussed.

**EXPERIMENTS IN FABRICATING HIGH EFFICIENCY CuInSe₂ SOLAR CELLS
BY SELENIZATION WITHOUT THE USE OF H₂Se**

D. Albin, J. Carapella, J. Tuttle, and R. Noufi
National Renewable Energy Laboratory

Selenization is a key process by which state-of-the-art CuInSe₂ polycrystalline thin-film photovoltaic devices and modules are fabricated. In this process, In + Cu layers deposited on glass substrates, referred to as precursors, are transformed into CuInSe₂ following exposure to a selenium-containing environment. In the past, industry has relied upon H₂Se as the major supplier of selenium in this process. However, this gas is highly toxic and consequently, alternative and more benign routes to selenization are desired. In this paper we present experimental results showing the use of elemental selenium as an alternative for H₂Se in producing high efficiency (10%) CdS/CuInSe₂ devices. In this process, competition between In-Se transport and surface kinetics as controlled by the thermodynamics of inter-phase reactions dominates precursor conversion into CuInSe₂. Finally, preliminary results based upon experiments using RF plasma techniques for non-H₂Se selenization will also be presented.

STATUS OF THIN FILM CIS SOLAR CELL TECHNOLOGY AT ISET

V.K. Kapur, B.M. Basol, A. Halani, and C. Leidholm
International Solar Electric Technology (ISET)

Since the last AR&D meeting, ISET has fabricated CIS solar cells (1 cm^2) with active area efficiency 12.3%. The structure of these heterojunction cells was glass/Mo/CIS/CdS/ZnO with light entering from the ZnO side. The open circuit voltages in some of these cells was observed to approach 500 mV and the highest value of the fill factor was observed to be 70%. The major challenge in increasing the efficiency of these solar cells has been to improve the short circuit current which was typically about 33 to 35 ma/cm^2 . The lower value of short circuit current was attributed to the reflective losses from the ZnO surface and some absorption in the ZnO film itself. Optimization of the ZnO film in terms of its reflective losses and absorption, is being carried out to obtain further gains in conversion efficiency.

ISET was awarded a U. S. patent in which the use of a thin ($\sim 100 \text{ \AA}$) layer of tellurium at the Mo/CIS interface to improve the adhesion between the CIS film and the Mo back contact was disclosed. Additionally the Te layer facilitated alloying of Cu and In layers and thus improved the compositional uniformity of CIS films.

ISET has also demonstrated the process for fabrication of a monolithically integrated CIS module (1 ft^2). A few process related problems were identified which need to be solved for lowering the cost of manufacturing and for improving the safety aspects of the overall module fabrication process. The paper will briefly discuss problems and the approaches that ISET is following to solve them.

DEGRADATION AND YELLOWING OF EVA IN PV MODULES

A.W. Czanderna

National Renewable Energy Laboratory

An overview will be presented of actual and potential materials degradation mechanisms by module encapsulation materials and at interfaces between them. The active semiconductor materials will not be included, except for their interfaces with encapsulation materials. Material durability is required for PV module reliability, and the degradation of the materials may result in a loss in the performance of the solar cells. Examples of actual degradation will be presented for ethylene vinyl acetate (EVA) photothermal degradation and metallization corrosion. The changes in the mechanisms of degradative reactions will be used to highlight the difficulty of predicting service lifetimes from accelerated life tests.

NOTES

SESSION III

THURSDAY A.M.

**FUNDAMENTAL STUDIES
OF PV MATERIALS**

SOLID STATE THEORY OF PV SEMICONDUCTORS

A. Zunger

National Renewable Energy Laboratory

In parallel with the time-honored, trial-and-error approach to solving technological problems, we have been using goal-oriented basic research techniques aimed at creating clear guidelines for selecting promising directions in PV research. Modern PV solar cells have reached a point of extreme material complexity, sometimes including in a single cell design structural elements such as superstructures, alloys, impurities, metal-semiconductor interfaces, interdiffused regions, partially-ordered and disordered segments, etc. Our basic premise is that a simultaneous study of all of these (and other) elements is unlikely to reveal clear and simple trends. Hence, we isolate the basic physical elements and study them one-by-one, e.g., the physics of alloys; superlattices; interfaces; etc. In this talk I will illustrate how modern methods of solid state theory have been applied in the past 1-2 years to clarify basic aspects of photovoltaic materials. Examples include: (1) How does the band gap of CuInSe_2 change depending on whether the material has the ordered chalcopyrite of the disordered sphalerite structure [1]. (2) How are the properties of semiconductor heterostructures affected by interfacial interdiffusion [2]. (3) How does surface reconstruction of $\text{Ga}_x\text{In}_{1-x}\text{P}$ alloys (present in MOCVD growth) lead to spontaneous ordering of such alloys, and how does this ordering affect light absorption [3].

Work supported by the U.S. Department of Energy under contract DE-AC02-83CH10093.

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**SPONTANEOUS COMPOSITION MODULATION:
A NEW TOOL FOR TAILORING THE OPTOELECTRONIC PROPERTIES OF
SEMICONDUCTOR ALLOYS**

A. Mascarenhas, R.A. Alonso, and G.S. Horner
National Renewable Energy Laboratory
K.C. Hsieh and K.Y. Cheng
University of Illinois

A recent experimental study on a $(\text{GaP})_2/(\text{InP})_2$ superlattice grown on a [001] GaAs substrate is described. The results of our measurements yielded the first experimental demonstration of the optoelectronic properties of a spontaneously generated lateral superlattice. A brief outline of the dynamics of the phenomenon of spontaneous lateral composition modulation is presented. It is proposed that this phenomenon can be utilized as a new tool for tailoring the optoelectronic properties of semiconductor alloys.

**OVERVIEW OF ORDERING AND RELATED ANOMALOUS
OPTICAL PROPERTIES OF $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$**

S.R. Kurtz, J.M. Olson, K.A. Bertness, D.J. Friedman
D.J. Arent, A.E. Kibbler, and C.M. Kramer
National Renewable Energy Laboratory

Under certain growth conditions, the single-crystal alloy $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$ spontaneously orders on the group III sublattice with gallium and indium atoms occupying alternating (111) planes. The ordered structure has been associated with variations in the observed bandgap, extra and moving optical transitions, anomalous polarization effects and very long low temperature photoluminescence lifetimes. The observed variations may be attributed to ordering or potential fluctuations associated with imperfect and nonuniform ordering and are a complex function of the growth parameters. Such anomalous optical properties may also be observed in other alloys that exhibit potential fluctuations, e.g., a-Si:H and CuInSe_2 .

TRAP-CONTROLLED H DIFFUSION MECHANISM IN a-Si:H

H.M. Branz, S.E. Asher, and B.P. Nelson

National Renewable Energy Laboratory

We report measurement of D profiles in a-Si:H/a-Si:H:D/a-Si:H structures after annealing treatments. When the temperature of the as-grown structure is raised, D is released from Si-D bonds to a transport level 1.4 eV higher. During the approach to equilibrium of the D system, D profiles include contributions from both the fixed (bonded) D and the mobile D. After equilibration, the diffusion coefficient of D is proportional to the density of mobile D. From our data, we calculate transport parameters for the mobile D, including its diffusion coefficient, mean free path, capture rate constant and retrapping time.

**MICROCHARACTERIZATION OF POLYCRYSTALLINE SEMICONDUCTOR
THIN FILMS FOR PHOTOVOLTAIC APPLICATIONS**

M.H. Bode, M.M. Al-Jassim, K.M. Jones, and F.S. Hasoon
National Renewable Energy Laboratory

Recent advances in the development of thin-film CuInSe₂ and CdTe based solar cells have pushed their efficiencies beyond the 14% mark. However, the properties of thin films of these materials are controlled by manipulations based on empirical studies, leaving many critical materials issues unresolved. Therefore, a detailed study of the structural and chemical characteristics of these films is required to further enhance the properties of these films.

In this work, we have investigated the properties of individual grains in polycrystalline thin films of CuInSe₂ and CdTe by transmission electron microscopy (TEM), transmission electron diffraction (TED), scanning electron microscopy (SEM) and energy dispersive x-ray spectroscopy (EDS) in the TEM.

The grain size of the polycrystalline CuInSe₂ films, as determined by SEM and plan-view TEM experiments, depends on the Cu concentration. This dependence is due to the presence of minor phases (Cu_xSe and In_ySe) whose nucleation and growth determine the grain structure of the film. Films with near stoichiometric composition have average grain size of ~ 1 μm and display an equiaxed morphology, often with faceted boundaries. Lowering the Cu content to ~ 17% decreased the grain size to <0.1 μm, while Cu₂Se has an average grain size of >2.5 μm. TED experiments to determine the crystal structure of individual grains showed that in near stoichiometric films most grains possess the chalcopyrite structure, which is expected for CuInSe₂. In some cases, however, weak additional spots were found, indicating the possibility of ordered phases. In the Cu rich films, a multitude of different phases could be found, some of which exhibited strong extra spots, due to twinning and/or ordering. To investigate the compositional changes across single grains, EDS spectra were taken at various locations on the grains. Using the total photon count as a measure of the local grain thickness and the ratio of Se_{Kα}/Se_{Lα} intensities to correct for absorption losses, we can normalize the Se_{Kα}, In_{Kα}, and Cu_{Kα} peak heights and thus analyze the

relative concentrations of Se, In, and Cu independently of grain thickness.

CdTe films, grown on a CdS/SnO₂/glass and examined by SEM showed that the grain size depends on the film thickness. While grains in 4 μm thick films were 1.5 - 3 μm in size, up to 20 μm grains could be found in films of 20 - 30 μm thickness. Cross-sectional examination revealed that the grains exhibited a smaller size and a more columnar structure close to the CdS/CdTe interface. These findings were supported by plan-view examination in the TEM. TEM experiments also revealed the type, density and distribution of the structural defects in this material. Threading dislocations, stacking faults, and twinned grains were frequently observed. However, their densities differed markedly from one grain to the next. Some grains exhibited defect densities in excess of 10⁹ cm⁻², while adjacent grains were virtually defect-free. The defect properties of these films will be correlated with the minority carrier lifetime and with the cell characteristics.

MINORITY-CARRIER LIFETIME OF COMPOUND SEMICONDUCTORS

B.M. Keyes, R.K. Ahrenkiel, and D.J. Dunlavy

National Renewable Energy Laboratory

The Electro-Optical Characterization Group of the National Renewable Energy Laboratory supports the photovoltaic community by characterizing the fundamental electrical and optical properties of semiconducting materials and devices. This presentation will discuss the usefulness of the time-resolved photoluminescence (TRPL) measurement technique by presenting data on a variety of polycrystalline CdTe material systems. By varying the conditions under which the data is obtained, we are able to distinguish between the various dominant recombination mechanisms and their corresponding lifetimes. The TRPL data will be correlated with measured cell efficiencies.

NOTES

SESSION IV (a)

THURSDAY P.M.

POLYCRYSTALLINE THIN FILMS

ANALYSIS OF HIGH EFFICIENCY CuInGaSe₂ BASED SOLAR CELLS

W.E. Devaney

Boeing Research & Engineering

A device with the structure ZnO/CdZnS/CuInGaSe₂ has been fabricated with a total area efficiency of 13.1% under AM1.5 equivalent test conditions as measured at NREL. The area of this device was approximately 1 cm².

This paper will review the fabrication of the various layers in the cell and then discuss the results of the analysis done to this date.

Detailed quantum efficiency and reflectance measurements have been made on both the high efficiency device and on cells fabricated using the same processes but yielding somewhat lower efficiencies. These results yield good estimates of the optical losses associated with the various layers of the device and also yield a good estimate of the thickness of the thin CdZnS layer in these devices. These and other results will be presented and discussed.

**COPPER-INDIUM-DISELENIDE PREPARED BY ELEMENTAL DEPOSITION
AND COMPOUND FORMATION: MATERIALS AND DEVICES**

R.R. Arya, T. Lommasson, L. Russell, S. Skibo, and A. Catalano
Thin Film Division
Solarex Corporation

A novel method has been developed for the preparation of copper-indium-diselenide (CIS) thin films. The method comprises of elemental deposition of Cu, In and Se layers followed by a CIS compound formation process which does not involve any H₂Se gas. The process has led to the formation of p-type CIS films which have proper stoichiometry and grain sizes on the order of 1 μm. Solar cells have been fabricated on this material employing the following device structure:

Light=>Metal Grid/ZnO/CdS/CIS/Mo/Glass

The best solar cell fabricated had an active area conversion efficiency of 10.2% with the following photovoltaic parameters:
 $V_{oc} = 0.427$ V, $J_{sc} = 37.41$ mA/cm² and FF = 0.641.

**A NEW, SELF-STABILIZING SELENIZATION PROCESS
FOR THE FORMATION OF CuInSe₂ SOLAR CELLS**

A. Delahoy, F. Faras, A. Sizemore, F. Ziobro, and Z. Kiss
Energy Photovoltaics, Inc.

Energy Photovoltaics (EPV), Inc. continues to refine its proprietary method for the formation of thin-film CuInSe₂. The technique involves the selenization of Cu-In multilayers by means not involving toxic H₂Se gas. Thus, the introduction of Se into sputtered and annealed Cu-In multilayers according to a specific temperature/time profile allows high-quality CIS crystal growth with automatic convergence of molecularity and valence stoichiometry to appropriate values. Devices having the structure glass/Mo/CIS/CdS/Zno:Al/metal grid typically exhibit V_{oc}, 420 mV, I_{sc} 35 mA/cm², and FF 60% for a CIS thickness of only 1 micron. The advantages of the EPV all-vacuum manufacturing process are: 1) self-stabilizing CIS composition, 2) efficient usage of materials, 3) reproducible, large-area high-throughput processing, and 4) reduced manufacturing hazards.

**INNOVATIVE DEPOSITION TECHNIQUES FOR THE FABRICATION
OF POLYCRYSTALLINE THIN-FILM PHOTOVOLTAICS***

J.H. Armstrong, B.R. Lanning, and M.S. Misra

Martin Marietta Astronautics

A key issue for photovoltaics (PV), both in terrestrial and future space applications, is producibility, particularly for applications utilizing a large volume of PV. Among the concerns for fabrication of polycrystalline thin-film photovoltaics, such as copper-indium-diselenide (CIS) and cadmium-telluride (CdTe), are production volume, which translates directly related to cost, and minimization of waste. Both the rotating cylindrical magnetron (C-Mag™) and pulsed electrodeposition have tremendous potential for the fabrication of polycrystalline thin-film photovoltaics due to scalability, efficient utilization of source materials and inherently higher deposition rates. In the case of sputtering, the unique geometry of the C-Mag™ facilitates innovative cosputtering and reactive sputtering that could lead to greater throughput, reduced health and safety risks, and ultimately lower fabrication cost. For pulsed electrodeposition, the films appear to be more tightly adherent and deposited at an enhanced rate when compared to conventional DC electrodeposition. This paper addresses Martin Marietta's investigation into innovative sputtering techniques and pulsed electrodeposition with a near-term goal of 930 cm² (1 ft²) monolithically-integrated CIS and CdTe submodules.

*This work was funded by Martin Marietta IR&D D-17R, "Photovoltaic Technologies" and NREL YG-1-11070-1, "Innovative Sputtering Techniques for CIS and CdTe Submodule Fabrication," Dr. Harin Ullal, Technical Monitor.

**NOVEL PROCESSING AND DEVICE STRUCTURES IN THIN-FILM
CuInSe₂-BASED SOLAR CELLS**

J.R. Tuttle, M. Contreras, A. Tennant,
A. Duda, D.S. Albin, and R. Noufi
National Renewable Energy Laboratory

We have developed a sequential process for the fabrication of enhanced-grain thin-film CuInSe₂-based photovoltaic devices. In this process, the necessity for exact control of the composition during fabrication is removed instead by modulating the interdiffusion of Cu and In between film layers of dramatically different molecularities. The resulting process of Cu₂Se to CuInSe₂ conversion in the bulk and the surface growth of the CuIn₂Se_{3.5} and CuIn₃Se₅ is dependent on both surface adatom concentrations and substrate temperature. Analysis of the film structures suggest enhanced grain size, transport, and photoconductivity. Device structures vary from one-sided heterojunctions to buried homojunctions where the window layer is not required for photo-response. In this paper, we present an update on this work and attempt to describe the relationship between the growth dynamics and the resultant material and device performance. The results suggest a new approach to the fabrication of high efficiency CuInSe₂-based solar cells. This work is performed under Contract No. DE-AC02-83CH10093 to the U.S. Department of Energy.

**ELECTRONIC PROPERTIES OF COPPER INDIUM DISELENIDE FABRICATED BY
TWO-STEP/SOLID SELENIUM PROCESSING**

L. Cai, G. Attar, and D.L. Morel
University of South Florida

Thin-film copper indium diselenide has been deposited using a two-step process with solid selenium as the Se source rather than H_2Se . Film properties are strongly influenced by the substrate. One micron thick films on 7059 glass have a grain size of about $0.1 \mu m$, while those on soda lime glass have a grain size of about $1 \mu m$. Electronic properties are similarly affected, particularly mobilities. Using MOSFET devices as analytical tools electron channel mobilities of up to $25 \text{ cm}^2/\text{Vs}$ have been measured in large grain samples, while the small grain samples exhibit drop in mobility by about a factor of 10. Preliminary results indicate that films on Mo/glass are equally influenced by the properties of the Mo, as expected.

**LARGE-GRAINED COPPER INDIUM DISELENIDE CRYSTAL GROWTH BY
COMPUTER-CONTROLLED HIGH-PRESSURE LEDS**

C.R. Schwerdtfeger and T.F. Cizek
National Renewable Energy Laboratory

Copper indium diselenide (CIS) has proven to be difficult to grow in single-crystal form. Some researchers believe cooling rates near $1^{\circ}\text{C}/\text{h}$ from around 1000°C to below 800°C are necessary to reduce ingot cracking. The sphalerite-chalcopyrite phase transition at 810°C may be the cause of such cracking. The author discusses preliminary results of CIS crystal growth done by high-pressure liquid-encapsulated direction solidification (LEDS) using a range of cooling rates from $3^{\circ}\text{C}/\text{h}$ to $20^{\circ}\text{C}/\text{h}$ in an effort to determine if run times can be reduced from the several weeks required to achieve $1^{\circ}\text{C}/\text{h}$ cooling rates in a $60^{\circ}\text{-}100^{\circ}\text{C}/\text{cm}$ temperature gradient to a more reasonable few days for higher rates.

POLYCRYSTALLINE HETEROJUNCTION SOLAR CELLS:

DEVICE PERSPECTIVE

J.E. Phillips, S.S. Hegedus, B.E. McCandless,
R.W. Birkmire, T.W.F. Russell, and W.N. Shafarman

Institute of Energy Conversion

University of Delaware

Modeling and analysis of both the current-voltage characteristics as a function of illumination intensity and temperature and the spectral response measurements as a function of voltage bias, indicate that both the $\text{CuInSe}_2/(\text{CdZn})\text{S}$ and CdTe/CdS solar cells operate as p-n heterojunctions with the current-voltage characteristic being controlled by either recombination at the metallurgical interface or by states within the space charge region of the CuInSe_2 or CdTe absorber-generator. Also, the polycrystalline nature of these materials allows for chemical reactions to take place at the grain boundaries this helps explain the reversible electronic doping caused by chemical reducing and oxidizing treatments.

POLYCRYSTALLINE HETEROJUNCTION SOLAR CELLS:

PROCESSING PERSPECTIVE

R.W. Birkmire, S.S. Hegedus, B.E. McCandless, J.E. Phillips,
T.W.F. Russell, W.N. Shafarman, S. Verma, and S. Yamanaka
Institute of Energy Conversion
University of Delaware

Developing an efficient commercial-scale process for fabricating large-area polycrystalline thin-film solar cells from a research process requires detailed understanding of the individual steps in making the solar cell and their relationship to device performance and reliability. In this paper, the complexities involved in characterizing a process are demonstrated with results from our research program on CuInSe_2 and CdTe processes. Specifically, the chemical pathways to formation of CuInSe_2 by selenization and their influence on film quality will be discussed with regard to the time-temperature profiles used in the process. The effect of high-temperature processing ($T > 400^\circ\text{C}$) of CdTe/CdS solar cells on the material and device properties will be described with regard to developing a well-controlled process.

TRANSIENT RESPONSE OF THIN-FILM POLYCRYSTALLINE SOLAR CELLS

R.A. Sasala, J.R. Sites, and X.X. Liu

Physics Department

Colorado State University

The voltage of both CuInSe_2 and CdTe cells continues to increase after either the onset of illumination or the switching of an illuminated cell is switched from closed- to open-circuit conditions. The magnitude of the time-dependent voltage is typically 20 to 50 mV. Time constants span several decades, 10^{-4} to 10^{+3} s, and are shorter at higher temperatures. The voltage shift is essentially the same at open-circuit and operating voltages. The shift depends primarily on the voltage history, not the illumination history, of the cell. The time-dependent response has implications for both device physics of cells and the interpretation of pulse simulator data.

**PHOTOEMISSION INVESTIGATION ON THE EFFECT OF In DOPING IN
CdS/CuInSe₂ HETEROJUNCTION FORMATION**

A.J. Nelson and D.W. Niles
National Renewable Energy Laboratory
D. Rioux, R. Patel, and H. Höchst
Synchrotron Radiation Center
University of Wisconsin-Madison

Synchrotron radiation soft x-ray photoemission spectroscopy was used to investigate the development of the electronic structure at the CdS(In)/CuInSe₂ heterojunction interface. In-doped CdS overlayers were deposited in steps on single-crystal *n*-type CuInSe₂ at 250°C. Results indicate that the CdS(In) grows in registry with the substrate, initially in a two-dimensional growth mode followed by three-dimensional island growth as is corroborated by RHEED analysis. Photoemission measurements were acquired after each growth in order to observe changes in the valence band electronic structure as well as changes in the In4d, Se3d, Cd4d and S2p core lines. The results were used to correlate the interface chemistry with the electronic structure at these interfaces and to directly determine the CdS(In)/CuInSe₂ heterojunction valence band discontinuity and the consequent heterojunction band diagram as a function of In dopant concentration. These results again show that indirect methods are unreliable in determining offsets for heterojunctions where significant Fermi level pinning may occur and where the local structure and chemistry of the interface depends strongly on the specific heterojunction.

**POLYCRYSTALLINE AND SINGLE CRYSTAL CuInSe₂: GROWTH, MICROSTRUCTURE,
AND ADHESION TO CONTACT METALLIZATIONS**

L.C. Yang and A. Rockett

The Coordinated Science Laboratory and
the Department of Materials Science and Engineering
University of Illinois

CuInSe₂ has been grown by the hybrid sputtering and evaporation process. Epitaxial CuInSe₂ on GaAs (001) and (111)-oriented substrates and exhibited (002) and (112) surface orientations, respectively. Faceting on (112) type planes with a clear preference for one of the sets of planes over the other was found. The facet structure depends on both the substrate surface preparation and the film stoichiometry. Ga and Cu diffuse across the heterojunction and voids formed spontaneously at the interface. Polycrystalline CuInSe₂ solar cell performances (current best, 8.4%) are generally limited by adhesion to the back contact. A significant improvement in adhesion has been achieved by the use of a Cu-Mo biphasic mixture as a back contact.

CuInSe₂ FORMATION BY RAPID ANNEALING OF THE ELEMENTAL PRECURSOR

A.M. Gabor and A.M. Hermann

University of Colorado

J. Tuttle and R. Noufi

National Renewable Energy Laboratory

Copper, indium, and selenium were coevaporated onto unheated molybdenum-coated substrates of glass and Al₂O₃. These substrates were then annealed in a Rapid Thermal Processor to form CuInSe₂. The films on glass substrates tended to peel upon annealing, but the films adhered well to the Al₂O₃. Working devices were made by evaporating CdS and top contacts onto the CuInSe₂. The device performance improved greatly with a 200°C air anneal. Work is underway to apply the technique of rapid annealing to precursors made by other, more scalable deposition methods.

NOTES

SESSION IV (b)

THURSDAY P.M.

III-V TECHNOLOGY

**EPITAXIAL PROCESSES AND STRUCTURES FOR
HIGH EFFICIENCY SOLAR CELLS**

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Departments of Electrical Engineering and Materials Science
and Engineering
University of Southern California

High-efficiency solar cells based on single- or multiple-junction designs require increasingly sophisticated epitaxial device structures. At the same time, there is increasing pressure to lower the cost of the cells. These contradictory developments place added requirements on the epitaxial processes that are used to fabricate the devices. In this talk, we will describe a new approach to epitaxial growth, vacuum atomic layer epitaxy (VALE) that potentially can solve this riddle by providing high-throughput epitaxial growth while maintaining atomic control of the layer thickness and uniformity. VALE uses the principle of saturated surface chemical reactions to deposit materials uniformly on a monolayer by monolayer basis. We will describe our current understanding of the surface chemistry of VALE and describe a VALE reactor design that we are studying. From our knowledge of the surface-reaction kinetics, we will describe the throughput potential of VALE and a reactor design that will make it possible to achieve this throughput. We will also describe the status of the materials development by this process.

In addition to the VALE work, we will also describe progress on the development of the epitaxial optical reflector solar cell concept. This device is a thin base solar cell concept that promises to increase the efficiency of solar cells by increasing the open circuit voltage through modification of the near-junction photocarrier profile.

**GALLIUM ARSENIDE HOMOEPITAXY EMPLOYING IN-SITU GENERATED
ARSINE RADICALS**

B.G. Pihlstrom, D.M. Shaw, A.D. Simone, L.R. Thompson,
T.Y. Sheng, and J. Lurkins

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Colorado State University

G.J. Collins

Research Laboratory of Engineering Materials
Tokyo Institute of Technology

K.M. Jones

National Renewable Energy Laboratory

An upstream hydrogen microwave plasma generates arsenic hydrides by etching the surface of solid arsenic. The hydrides are transported to the deposition region and mixed with trimethylgallium to achieve low-temperature (350-400°C) and low-pressure (750 mTorr) homoepitaxial GaAs films. Low precursor V/III ratios are used to achieve homoepitaxial films with high levels of carbon dopants. No plasma exists in the growth region. The observed homoepitaxial growth activation energies of 54 kcal/mole and 66 kcal/mole for films deposited with V/III ratios of 1/1 and 1/4, respectively, are in the range of those reported for the heterogeneous decomposition of trimethylgallium in the absence of arsine. The films are found to be of good crystalline quality via both double crystal x-ray rocking curves and transmission electron microscopy. The majority carriers are holes and have hole concentrations that correlate to the carbon doping, as determined by room-temperature Hall effect measurements and secondary ion mass spectroscopy.

ECR-PLASMA-ASSISTED HETEROEPITAXY OF CuInSe_2 ON ZnTe

B. J. Stanbery

The Boeing Company

The heteroepitaxial growth of CuInSe_2 on ZnTe by MBE utilizing an Electron Cyclotron Resonance (ECR) cracking cell for the selenium molecular vapor will be reported.

The ECR-PAE technique is being developed in order to significantly reduce the growth temperature for single crystal CuInSe_2 . Growth temperature reduction is expected to reduce copper diffusion and improve the incorporation of selenium.

Mitigating the indiffusion of Cu into the substrate is important for the fabrication of useful devices which incorporate active semiconductor layers in which copper is a deep-level defect. Limited diffusion of copper into ZnTe may be useful for the formation of a heterojunction between the two semiconductors, since copper is an acceptor in ZnTe .

CuInSe_2 is a ternary chalcopyrite semiconductor whose electrical properties are believed to be dominated by electrically active native defects resulting from deviations from a stoichiometric composition. Limiting copper self-diffusion in CuInSe_2 should improve control of composition gradients within the CuInSe_2 epilayer, thereby permitting effective carrier density profile control.

**PERFORMANCE AND CHARACTERISTICS OF A REACTOR
FOR SOLAR CELL MATERIALS GROWTH**

P.B. Chinoy, I.B. Bhat, J.M. Borrego, and S.K. Gandhi
Electrical, Computer and Systems Engineering Department
Rensselaer Polytechnic Institute

The design of a novel inverted reactor for large-area epitaxial growth was described at the last PV AR&D meeting. This design was based on computer-derived predictions of low nozzle temperature, and laminar flow in the vicinity of the susceptor. This talk will emphasize the operational characteristics of this reactor.

Both doped and undoped GaAs have been grown on this system. A growth layer uniformity of $\pm 5\%$ and a doping uniformity of $\pm 3.3\%$ have been obtained over 2" diameter slices. Computer simulations show that the growth uniformity is strongly dependent on the thickness of the lip which is used to hold the substrate in an inverted position. A minority-carrier bulk lifetime of 240 ns has been obtained, based on measurements of $n^+ - n - n^+$ structures.

**RADIATIVE RECOMBINATION AND PHOTON RECYCLING
IN GaAs SOLAR CELLS**

M.S. Lundstrom, M.R. Melloch, G.B. Lush, M.P. Patkar, M. Young,
S.M. Durbin, and J.L. Gray

Purdue University, School of Electrical Engineering

J.F. MacMillan

Varian Research Center

B.M. Keyes, D.H. Levi, and R.K. Ahrenkiel

National Renewable Energy Laboratory

This talk reviews experimental work to develop a detailed understanding of radiative recombination in n-GaAs. Photoluminescence decay studies of minority-carrier lifetimes versus doping in n-GaAs are presented. We show that when the substrate is removed by etching, photon recycling is enhanced, and lifetimes increase by nearly a factor of 10. The doping-dependent absorption coefficient is measured, and detailed balance arguments are used to relate absorption and recombination. Modeling studies, verified by comparison with experiments, are used to examine the effects of recycling in conventional solar cells and to explore new design options.

**MOCVD GROWTH OF GaAs STRUCTURES FOR SOLAR CELLS
ON SILICON SUBSTRATES**

S.M. Vernon, N.K. Karam, T.P. Parodos, V.E. Haven, L.M. Geoffroy,
M.M. Sanfacon, and A.L. Mastrovito
Spire Corporation

This paper reports advances in the development of solar cells made from GaAs-on-Si structures prepared by metal organic chemical vapor deposition (MOCVD). The use of concentrator cells, operating at ~200 suns, has led to the efficiency achievements of 21.3% (AM1.5D) for a GaAs-on-Si solar cell, and 27.6% (AM1.5D) for a homoepitaxial GaAs cell. The development of epitaxial multilayer dielectric mirrors (Bragg reflectors), as back-surface reflectors in thin-film GaAs cells, on both Si and GaAs substrates, is shown to lead to modest efficiency increases, over that of conventional designs. Defect-density reduction in GaAs-on-Si films, by use of a novel substrate-patterning approach, is also reported.

HIGH-EFFICIENCY THIN-FILM SOLAR CELLS

R.P. Gale, J.V. Gormley, B.D. King, and R.W. McClelland
Kopin Corporation

The application of the CLEFT thin-film technique to GaInP/GaAs solar cells and organometallic overgrowth has been investigated. Growth experiments were carried out using tertiarybutylphosphine (TBP) as the group 5 source, resulting in GaInP layers grown lattice-matched to GaAs. The layers had good surface morphology and exhibited strong room-temperature photoluminescence. Solar cell structures have been grown and fabricated. In parallel, conditions for the in situ overgrowth by OMCVD have been determined and continuous GaAs layers grown over a separation mask layer. Several of these layers have subsequently been successfully cleaved from their substrates.

DEVELOPMENT OF GaInAsP FOR GaInAsP/Ge CASCADE SOLAR CELLS

P.R. Sharps, M.L. Timmons, R. Venkatasubramanian, R. Pickett,
J. Hancock, and J.S. Hills
Research Triangle Institute

Quaternary semiconductor compounds are ideal candidates for use in multijunction cascade solar cells because the lattice constant and the band gap of such compounds can be independently varied. The quaternary semiconductor compound $\text{Ga}_{0.38}\text{In}_{0.17}\text{As}_{0.67}\text{P}_{0.33}$ not only is lattice-matched to Ge but also provides a current matched top cell for the GaInAsP/Ge monolithic cascade solar cell. Under concentration of 100 suns, the projected efficiency for such a cell is about 35%. The growth of $\text{Ga}_{0.83}\text{In}_{0.17}\text{As}_{0.67}\text{P}_{0.33}$ lattice-matched to Ge has been demonstrated, and $\text{Ga}_{0.83}\text{In}_{0.17}\text{As}_{0.67}\text{P}_{0.33}$ solar cells with 1-sun AM 1.5 efficiencies of 18.8% have been grown on GaAs. Different issues in the development of the GaInAsP/Ge cascade cell will be discussed, including the optimization of the $\text{Ga}_{0.83}\text{In}_{0.17}\text{As}_{0.67}\text{P}_{0.33}$ solar cell, the optimization of the Ge solar cell, and the development of the tunnel junction interconnect.

DEVELOPMENT OF AN IR-TRANSPARENT, INVERTED-GROWN, THIN-FILM

$\text{Al}_{0.37}\text{Ga}_{0.63}\text{As}/\text{GaAs}$ CASCADE SOLAR CELL

R. Venkatasubramanian, M.L. Timmons, P.R. Sharps,

T.S. Colpitts, J.S. Hills, and J.A. Hutchby

Research Triangle Institute

Inverted growth of III-V solar cells and the development of associated cell processing, including substrate removal, offers a significant degree of freedom for improving the performance of many multijunction cascades. This is especially true for the development of high-efficiency $\text{Al}_{0.37}\text{Ga}_{0.63}\text{As}/\text{GaAs}$ cascades where the high growth temperatures required for the AlGaAs top cell growth can cause the deterioration of the tunnel junction interconnect. In the approach of inverted-grown AlGaAs/GaAs cascade cells, the AlGaAs top cell is grown first at high temperatures and the GaAs tunnel junction and bottom cell are grown at lower temperatures. After the inverted growth, the AlGaAs/GaAs cascade structure is selectively removed from the parent substrate. The development of such a cascade cell takes advantage of the progress made in obtaining significantly improved $\text{Al}_{0.37}\text{Ga}_{0.63}\text{As}$ cells at 780°C , a high-conductance planar GaAs tunnel junction interconnect, and thin-film GaAs-AlGaAs structures by a combination of eutectic-metal-bonding and selective Ge substrate-removal. A GaAs cell with a 1-sun AM1.5 efficiency of 19.2% has been initially demonstrated to assess the feasibility of thin-film, inverted-grown cells. Various issues in the development of high-efficiency, inverted-grown $\text{Al}_{0.37}\text{Ga}_{0.63}\text{As}/\text{GaAs}$ cascades will be outlined and electrical characteristics of these cascades will be discussed.

GaInP₂/GaAs TANDEM CELLS: PROBLEMS AND SOLUTIONS

J.M. Olson, Sarah Kurtz, A.E. Kibbler, D.J. Friedman,
K.A. Bertness, and C. Kramer
National Renewable Energy Laboratory

The tandem combination of a GaInP₂ top cell and a GaAs bottom cell has a practical theoretical efficiency of 30% at one sun and 34.5% at 1000 suns. In the course of this work we have discovered a number of interesting problems that limit the efficiency of this device, including a bottom cell-tunnel junction interaction and a deep level in GaInP and AlGaInP associated with carbon. In some cases, these may be problems that can affect the efficiency of other tandem cells.

PHOTOLUMINESCENCE EXCITATION AND SELECTIVELY EXCITED PL IN ORDERED
AND DISORDERED $\text{Ga}_{0.52}\text{In}_{0.48}\text{P}$

M.C. DeLong¹, R.A. Hogg[†], D.J. Mowbray[†], M. Hopkinson^{*},
and M.S. Skolnick[†]

Departments of Physics[†] and Electrical and Electronic Engineering^{*}
University of Sheffield

P.C. Taylor

Physics Department, University of Utah

J.M. Olson

National Renewable Energy Laboratory

The band gap of $\text{Ga}_{0.52}\text{In}_{0.48}\text{P}$ varies considerably, depending on conditions of growth. This is a result of ordering in the CuPt structure. Details of the ordering also lead to more subtle optical effects. We will report here on photoluminescence excitation (PLE) and selectively excited PL measurements on ordered and disordered $\text{Ga}_{0.52}\text{In}_{0.48}\text{P}$. The dominant high-energy emission process in disordered GaInP has been established to be excitonic, but the exciton trapping energy is not unique. PLE from ordered $\text{Ga}_{0.52}\text{In}_{0.48}\text{P}$ shows significant tailing of electronic states and a "band edge" that depends on detection energy.

¹Permanent address: Physics Department, University of Utah

**ATOMIC LAYER EPITAXY OF AlGaAs/GaInP HETEROJUNCTION TUNNEL
DIODE FOR CASCADE SOLAR CELLS**

D. Jung, C.A. Parker, J. Ramdani, M. Leonard, N.A. El-Masry
and S.M. Bedair

Department of Electrical and Computer Engineering
North Carolina State University

High levels of n^+ -doping is usually difficult to achieve in high-band gap ($E_g > 1.8$ eV) III-V compounds, presumably because of the presence of DX centers. We used the ALE growth mode to achieve doping levels of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ ($E_g \approx 1.9$ eV) in the high $10^{19}/\text{cm}^3$ range.

This n^+ -GaInP film was incorporated in a p^+ -AlGaAs/ n^+ -GaInP heterojunction tunnel diode. The $\text{Al}_{0.36}\text{Ga}_{0.64}\text{As}$ was carbon-doped to $1 \times 10^{20}/\text{cm}^3$ utilizing the ALE approach, in which CH_3 originated from OM sources. The I-V characteristics show a peak voltage at about 135 mV at room temperature. At $15 \text{ A}/\text{cm}^2$, which is the approximate current density for an AlGaAs/GaAs two junction solar cell operating at 1000 suns, the voltage drop across the tunnel junction is only ~17 mV.

We report on the properties of these highly doped materials and on the characteristics of the tunnel diode.

RECENT DEVELOPMENTS IN GaAs/GaSb TANDEM CELL TECHNOLOGY

L.M. Fraas, V. Sundaram, P. Gruenbaum,
M. Kuryla, D. Pietila, and J. Avery
Boeing High Technology Center

We have previously reported the fabrication of mechanically stacked GaAs/GaSb tandem cells with efficiencies over 30% measured at the cell level. Over the last year, we have been working on (1) methods of manufacturing these cells in quantity at lower cost, and (2) the development of high efficiency concentrator modules utilizing these cells. Some of our specific accomplishments in these areas are as follows: (1a) The fabrication of high performance GaAs cells utilizing zinc diffusions. (1b) The reduction of grid-line shading losses using grids with triangular-shaped cross sections. (2a) The fabrication of stacked cells with a 10 micron-thick glue line for high thermal conductivity and laser TAB bonded leads for testability and high-throughput assembly. (2b) The fabrication of triplet minimodules with over 25% efficiency (50x, AM0) including lens losses.

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SESSION IV (c)

THURSDAY P.M.

AMORPHOUS SILICON

**SMALL-ANGLE X-RAY SCATTERING STUDIES OF THE MICROSTRUCTURE
OF a-Si:H AND RELATED ALLOYS**

S.J. Jones, Y. Chen, and D.L. Williamson

Department of Physics
Colorado School of Mines

Small-angle x-ray scattering (SAXS) measurements are being made to probe the microstructures on a scale from about 1 to 25 nm of amorphous silicon and silicon-based alloy films prepared in several laboratories using a variety of deposition techniques. Assuming a film structure composed of voids dispersed in an amorphous network, sizes and volume fractions of the voids are determined while measurements of the films at various tilt angles relative to the x-ray beam give information on the shapes and orientations of the voids. This microstructural information determined by SAXS is being correlated with various opto-electronic properties to help establish whether such microstructure may be limiting solar cell efficiency and stability.

AN ATOMIC SCALE PICTURE OF THE GROWING a-Si:H SURFACE

A. Gallagher

National Institute of Standards and Technology

The properties of a-Si:H photovoltaics depend on structural imperfections and irregularities in the deposited film, as well as on the bonding character at these sites and at interfaces. We are studying the character of the irregularities as they appear in the growing film surface, using a scanning tunneling microscope (STM) to observe them with atomic resolution. Film is glow-discharge deposited on atomically flat crystal Si and GaAs, then the substrates are cooled and transferred into the STM without breaking vacuum. A variety of surface topologies will be shown, for a variety of deposition conditions and film thicknesses.

**SPECTROSCOPIC STUDIES OF a-Si:H, a-Si_{1-x}C_x:H, AND
a-Si_{1-x}N_x:H ALLOYS**

P.C. Taylor

Department of Physics

University of Utah

Measurements using light well below the optical band gap (≥ 1.1 eV) show that the low temperature PL efficiencies per absorbed photon increase dramatically at low excitation energies. This result has important consequences for our understanding of how photoexcited carriers are distributed at low temperatures in the band-tail states in a-Si:H. PL experiments in nitrogen-rich a-Si_{1-x}N_x:H alloys support the suggestion that the dominant deep defect may possess a negative electron-electron correlation energy. Absorption and PL measurements in n-type a-Si:H alloys (using a liquid organic source) suggest a possible mechanism for widening the band gap in n-type doped layers.

DEFECT STATES IN AMORPHOUS AND MICROCRYSTALLINE Si

G. Lucovsky, B.N. Davidson, and S.M. Cho

Departments of Physics, and Materials Science and Engineering
North Carolina State University

This paper discusses two aspects of intrinsic defect states: (1) the application of the tight-binding method to dangling bond defects in hydrogenated amorphous Si, and Si,Ge alloys (a-Si:H and a-Si,Ge:H, respectively); and (2) the effect of dangling bonds in the amorphous Si component of microcrystalline Si ($\mu\text{c-Si}$) on the interfacial electrical properties at the interface between the crystalline and amorphous constituents of the microcrystalline material. The results of these studies are combined to provide insights into differences between light-fatigue (the Staebler-Wronski effect) in a-Si:H and $\mu\text{c-Si:H}$.

**ELECTRICAL AND OPTICAL PROPERTIES OF DOPED TIN AND ZINC OXIDE
THIN FILMS BY ATMOSPHERIC PRESSURE CHEMICAL VAPOR DEPOSITION**

J Hu and R.G. Gordon
Department of Chemistry
Harvard University

Zinc oxide and tin oxide films have been deposited by atmospheric pressure chemical vapor deposition. Zinc oxide films doped with fluorine have higher mobility and higher visible transmission than those doped with the Group III elements (B, Al, Ga). A ZnO:F film with a sheet resistance of 5 Ω /square has an average visible absorption of about 3% and a visible transmittance up to 90%. Various doped zinc oxide films were compared with each other and with SnO₂:F films through their Figure of Merit, which is defined as the ratio of the conductivity over the visible absorption coefficient. Zinc oxide films doped with fluorine have the highest Figure of Merit and are very promising as transparent electrodes for solar cells with high cell efficiency.

PROPERTIES OF AMORPHOUS SILICON DEPOSITED AT HIGHER TEMPERATURES

V.L. Dalal

Iowa State University

We describe a new technique, Reactive Plasma Beam Epitaxy, for growing a-Silicon films at higher temperatures. The technique uses a reactive beam of H atoms and ions, produced using an Electron Cyclotron Resonance (ECR) plasma source, to decompose SiH_4 and deposit films and devices. We find that the quality of the films depends critically upon the flux of H radicals reaching the substrate. Control over this flux allows us to grow high-quality films even at temperatures of 375°C . We find that these films are more stable than comparable quality films deposited by glow discharge at lower temperatures, presumably due to a better local microstructure created by higher growth temperatures. The films have very good electronic qualities. We have also made preliminary p-i-n superstrate devices in these materials. The quantum efficiency data indicate that the hole diffusion lengths in these materials are quite good, with hole $\mu\tau$ products being in the range of 3 to $4\text{E-}8$ cm^2/sec .

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SESSION IV (d)

THURSDAY P.M.

**APPLICATION OPPORTUNITIES
FOR PV**

PV OPPORTUNITIES IN COLORADO

J.P. Thornton

National Renewable Energy Laboratory

PV systems have penetrated an increasing number of utility applications. Although when compared to the overall electrical demand of the U.S., the capacity deployed to date is very small, this penetration represents an important step in the development of PV as a utility resource. PV can be more reliable or cost-effective than other alternatives in many urban or rural situations including remote standalone, extension line/transformer upgrades, replacement of hard-to-maintain extension lines, and avoidance of high labor cost operations. This paper provides a quick overview of some Colorado projects already deployed or under consideration.

**THE ROLE OF PV IN DEMAND-SIDE MANAGEMENT:
POLICY AND INDUSTRY CHALLENGES**

J. Byrne

Center for Energy and Urban Policy Research
University of Delaware

Most electric utility planners consider photovoltaics to be a frontier technology which is not yet mature enough to contribute to the U.S. electric generation market. Over the past decade, utilities and their regulators have begun to emphasize demand-side management (DSM) to meet an increasing proportion of their service needs. For PV to be a valued technology in the electricity sector, DSM applications need to be identified that can provide a significant market for this technology. DSM programs of 25 of the most active utilities in the DSM market are analyzed in this research to determine the size, prices, demand, and impact of policy. Target PV-DSM markets are identified and the policy and industry challenges that must be met are defined.

PVUSA - CURRENT STATUS

C. Jennings

Pacific Gas and Electric Company

Photovoltaics for Utility Scale Applications (PVUSA) is a cooperative project involving utilities, the PV industry, the U.S. government, and other agencies to identify, test, and report on state-of-the-art PV module and system technologies directed toward cost-effective utility-scale applications. This presentation will include highlights documented in the *PVUSA 1991 Progress Report*, early 1992 accomplishments, outstanding issues, and future plans.

**EVALUATION OF SATELLITE-BASED SOLAR RESOURCE ASSESSMENT
FOR INVESTIGATING UTILITY LOAD MATCHING**

R. Perez, R. Seals, and R. Stewart
Atmospheric Sciences Research Center
State University of New York at Albany

This paper reports on the first phase of an NREL-supported effort investigating the interaction between photovoltaics (PV) and U.S. electric utilities. Attention is focused on evaluating the ability of remote solar resource assessment from geostationary satellites to address the interaction issue satisfactorily.

A pilot study in New York State concluded that despite a non-negligible scatter between satellite irradiance estimates and ground-based irradiance measurements, the satellite data were accurate enough to provide an adequate estimation of the load matching capability of PV.

In this paper, we report on an extension of this pilot study to climatically distinct sites in the United States. We show that results remain consistent and conclude that it is reasonable to proceed with a U.S.-wide evaluation of PV-utility load matching opportunities using available satellite data.

Acknowledgments

This work is supported by NREL under Contract #XR 1111681 with additional support from the Mobil Foundation.

NEW CAPABILITIES FOR SOLAR RESOURCE ASSESSMENTS

D.S. Renné

National Renewable Energy Laboratory

NREL's Solar Radiation Resource Assessment Project (SRRAP) is completing a new national solar radiation data base to replace the earlier SOLMET/ERSATZ data. The new data base will contain hourly direct, diffuse, and global solar data for about 50 measured and 200 modeled sites in the U.S. for the period 1961-1990. By combining this data base with other information, a number of solar resource assessment products will be produced by the SRRAP over the next few years which will provide direct assistance to the solar community. This paper presents an overview of the data base, and the products and the products anticipated for development.

SUNRAYCE 93*

C. Leboeuf

National Renewable Energy Laboratory

Sunrayce 93 is a DOE-sponsored, intercollegiate competition of solar-powered cars which is open exclusively to colleges and universities in North America. Sunrayce is an ongoing educational program that will culminate every two years with race participation. Thirty-six teams have been selected to compete in the 1000-mile race to be held in June of 1993. These teams represent 20 states (including Hawaii), as well as the District of Columbia, Puerto Rico, and Canada. Each team will devote hours both in and outside the classroom with activities that include planning, fund raising, design, and construction. The goal is to build a reliable, solar-powered car to compete against fellow students. As an applied engineering project, Sunrayce is a successful educational motivator for students in the areas of math, science, and engineering. The race, which will be held during the summer solstice week in 1993, begins in Dallas and travels through Oklahoma City, Tulsa, Kansas City, Des Moines, and concludes in Minneapolis.

*This work is supported by the U.S. Department of Energy under Contract No. DE-AC02-83CH10093.

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SESSION V (a)

FRIDAY A.M.

**POLYCRYSTALLINE THIN FILMS
(continued)**

**AN IMPROVED UNDERSTANDING OF EFFICIENCY LIMITING DEFECTS IN
POLYCRYSTALLINE CdTe/CdS SOLAR CELLS**

A. Rohatgi, A. Bhat, and H.C. Chou
School of Electrical Engineering
Georgia Institute of Technology

Efficiency-limiting mechanisms associated with CdS substrates, CdCl₂-treated CdTe films, and Cu/Au contacts were investigated. It was found that thermal treatment of CdS films prior to CdTe deposition removed oxygen-related defects in these films. However, it also created nonuniform and Cd-deficient CdS surfaces. Cd-rich conditions retarded the interdiffusion between CdTe and CdS and maintained the band gap at 1.5 eV. CdCl₂ treatment on CdTe improved the cell performance significantly. However, it also produced defects at $E_v + 0.64$ and $E_v + 0.17$ eV which are probably due to V_{Cd} -Cl complexes. An inverse correlation was found between the density of these defects and V_{oc} . Finally, a rapid initial degradation was observed in the higher efficiency (10-12%) CdTe cells with Cu/Au contacts and a bromine-methanol etch was found to restore the cell performance.

HIGH TEMPERATURE VAPOR DEPOSITION OF THIN FILM CdTe PV MODULES

P.V. Meyers

Solar Cells, Inc.

Solar Cells, Inc. (SCI) has a program to produce 60 cm × 120 cm solar modules based on CdTe films deposited by close-spaced sublimation and chemical vapor deposition using elemental sources. Small area efficiency has been confirmed by NREL at 9.3% on a 0.22 cm² device (825 mV Voc, 18.16 mA/cm² Jsc, and 0.62 FF) deposited on a 100 cm² substrate. Preliminary work has begun on the fabrication of 8 cell, 64 cm² submodules. ZnTe, CdTe, and CdS films have been deposited onto 60 cm × 120 cm substrates—small area devices produced from this material have exceeded 8% efficiency.

THIN-FILM CdTe PHOTOVOLTAIC CELLS BY LASER DEPOSITION

A. Compaan, R.G. Bohn, A. Bhat, C. Tabory, M. Shao, Y. Li,
M.E. Savage, and L. Tsien

Department of Physics and Astronomy

The University of Toledo

Laser-driven physical vapor deposition (LDPVD) and radio-frequency (rf) sputtering have been used to fabricate thin-film solar cells on SnO₂-coated glass substrates. The laser-ablation process readily permits the use of several target materials in the same vacuum chamber and complete solar cell structures have been fabricated on SnO₂-coated glass using LDPVD for the CdS, CdTe, and CdCl₂. To date, the best devices (~9% AM1.5) have been obtained after a post-deposition anneal at 400°C. In addition, cells have been fabricated with the combination of LDPVD CdS, rf-sputtered CdTe, and LDPVD CdCl₂. The performance of these cells indicates considerable promise for the potential of rf sputtering for CdTe photovoltaic devices. The physical mechanisms of LDPVD have been studied by transient optical spectroscopy on the laser ablation plume. These measurements have shown that, for example, Cd is predominantly in the neutral atomic state in the plume but with a large fraction which is highly excited internally (≥ 6 eV) and that the typical neutral Cd translational kinetic energies perpendicular to the target are 20 eV and greater. The quality of as-grown and annealed films has been analyzed by optical absorption, Raman scattering, photoluminescence, electrical conductivity, the Hall effect, x-ray diffraction, and SEM/EDS.

SOLUTION GROWN CdS THIN FILMS FOR SOLAR CELLS

K. Ramanathan, R.G. Dhere, T.J. Coutts, T. Chu, and S. Chu
National Renewable Energy Laboratory

CdS thin films were grown from dilute solutions of cadmium acetate and thiourea. The concentration of ammonium acetate was varied, and its effect on the optical properties was studied. Nucleation and structural characteristics of films grown on glass, tin-oxide-coated glass and CuInSe₂ thin films were investigated. With increasing ammonium salt concentration, an increase in the absorption and a down-shift of the energy gap of CdS were found to occur. Films produced from acetate baths were less absorbing than those from chloride baths. The refractive index of the films, deduced from ellipsometry measurements, was found to be sensitive to the porosity of the films. The use of dilute solutions permitted the observation of CdS growth on CuInSe₂ films. The interference color provided a good estimate of the thickness of the CdS coating and, hence used as an end point indicator. The properties of thin CdS films and their influence on the CdS/CuInSe₂ and CdS/CdTe devices will be discussed.

This work was performed for the U.S. Department of Energy under Contract No. DE-AC02-93CH10093.

ION AND PHOTON ASSISTED GROWTH AND DOPING OF CdTe FILMS

A.L. Fahrenbruch, D. Kim, A. Lopez-Otero, and R.H. Bube

Department of Materials Science and Engineering

Stanford University

Previous work demonstrated doping to $2 \times 10^{17} \text{ cm}^{-3}$ with 60 eV P ions during growth by vacuum deposition, but with a decrease in the minority-carrier diffusion length L_d . To obtain longer L_d , we attempted photon-assisted doping, varied the Cd/Te ratio, and used lower ion energies. Although illumination during growth enhanced crystalline quality, there was no evidence for an increase in doping. Increased Cd/Te ratio ($1.00 < \text{Cd/Te} < 1.4$), both with and without ions and/or light during deposition, changed the In/p-CdTe junction transport, but gave no useful alteration of the doping behavior. Using 20 eV P ions with an electron flux has thus far yielded doping up to $6 \times 10^{16} \text{ cm}^{-3}$ with a substantially increased L_d .

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SESSION V (b)

FRIDAY A.M.

PV PERFORMANCE AND TESTING

EFFICIENCY MEASUREMENTS ON THIN-FILM PV CELLS AND MODULES

K. Emery

National Renewable Energy Laboratory

Substantial differences in the measured I-V characteristics of thin-film devices can occur because of premeasurement conditions, bias rate, bias direction, contacting, spatial uniformity of the light source, and algorithms to obtain the maximum power. Measurement techniques developed at NREL to identify and minimize these effects are described with examples for several of the more promising PV technologies. Multijunction thin-film devices are subject to large uncertainties if the spectral irradiance is uncontrolled. Procedures have been developed that correct for these problems for small areas, but have not been developed for measurement systems using pulsed light.

This work was supported by the U.S. Department of Energy under Contract DE-AC02-83CH10093.

THIN-FILM PV MODULE TESTING AT NREL

L. Mrig, Y. Caiyem, D. Waddington
National Renewable Energy Laboratory

Testing thin-film modules significantly contributes to the understanding of the field performance and reliability of emerging PV technologies. A number of programs are in operation at NREL for testing flat-plate PV modules and monitoring their performance in sunlight and in simulated conditions to provide accelerated performance characteristics of long-term exposure to normal weather conditions. Modules are installed outdoors and are connected to loads so that their performance in an "in service" condition can be monitored. Other modules are mounted in environmental chambers and are exposed to the rigors of heating, freezing, and high humidity. Modules are exposed to simulated rain and tested for electrical leakage and also are exposed to simulated hailstones to determine structural integrity. Performance tests are conducted under standard test conditions (STC) in accordance with ASTM E1036. This paper will present some of the details of PV module testing at NREL.

INVESTIGATION OF EVA DEGRADATION MECHANISMS

F.J.J. Pern and A.W. Czanderna

Measurements and Characterization Branch

National Renewable Energy Laboratory

Yellow-browning of the ethylene vinyl acetate (EVA) copolymer encapsulant used in PV modules has resulted in a significant power loss up to more than 50% of the initial power output. The weathering-degraded yellow-brown EVA films have lost the ultraviolet (UV) absorber, Cyasorb UV 531, and the degree of cross-linking (gel content) has increased. The EVA degradation mechanisms are discussed in this work. Upon exposure to UV light at 45°-85°C, the virgin EVA films that are stabilized with Cyasorb UV 531 and two antioxidants show an increase in the gel content, a gradual loss of Cyasorb by photooxidation, and generation of acetic acid. The deacetylation reaction, which leads to the formation of polyenes, also occurs significantly in the films heated in the dark at 130°C for five days. The acetic acid is found to thermally catalyze the EVA film discoloration at 85°-130°C, which increases from a light yellow to a yellow-brown color as the heating temperature increases. These factors can account for the yellow-browning of the EVA in the acceleration-tested mini-modules; the yellow-browning is more profound when exposed to UV light at 85°C than when heated in the dark at the same temperature. In the presence of the EVA-produced acetic acid and oxygen, and with sunlight exposure, the Cu buslines that were coated with a thin layer of Pb-Sn alloy show significant oxidation and metal interdiffusion, which in turn may have contributed to the resistance increase and hence the current loss observed in the weathered PV modules.

AN OVERVIEW OF NREL'S PV SOLAR RADIATION RESEARCH ACTIVITIES AND RESULTS

R. Hulstrom, T. Cannon, T. Stoffel, and C. Riordan
National Renewable Energy Laboratory

NREL's PV solar radiation research task is in direct support of characterizing, measuring, testing, designing, and understanding the performance of PV cells, submodules, modules, and systems. A scientific and engineering understanding of incident solar irradiance and the development of instrument systems and measurement methodologies are the major activities of the solar radiation research task. An overview of major accomplishments, over the previous 18 months, is presented. This includes the Atmospheric Optical Calibration System (AOCS), a joint project with the Electric Power Research Institute (EPRI) to compare several solar radiation measurement systems as options for resource assessments in a utility's service territory, and projects to design, install, and operate monitoring stations at two selected utility sites.

PHOTOVOLTAIC STANDARDS DEVELOPMENT WITHIN ASTM

C.R. Osterwald

National Renewable Energy Laboratory

ASTM subcommittee E44.09 is actively involved in developing and revising industry-consensus standards for photovoltaics. Current standards and draft documents fall into three categories: photovoltaic reference cell calibration, device and module characterization, and module environmental testing. This paper presents the current status of all E44.09 draft documents and standards and describes an interlaboratory intercomparison that is needed for reapproval of several existing standards. The interlaboratory intercomparison will be conducted in 1992.

Preparation of this paper is performed under Contract No. DE-AC02-83CH10093 to the U.S. Department of Energy.

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SESSION V (c)

FRIDAY A.M.

CRYSTALLINE SILICON

IMPROVED LIFETIMES AND 14% SOLAR CELLS FROM EFG SILICON SHEET

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Recent improvements in crystal growth have led to increases in the lifetime of as-grown crystalline silicon produced by the edge-defined film-fed growth (EFG) technique. As-grown EFG sheet bulk lifetimes, as measured by a noncontact photoconductive decay (PCD) technique, have increased to over 10 microseconds. These improvements have allowed large batches of 10 cm x 10 cm EFG solar cells to be made with efficiencies averaging close to 14%. The best of these cells have bulk diffusion lengths in the range of 300 to 600 microns, which are of the order of the sheet thickness. These developments raise the possibility of achieving even higher EFG cell efficiencies if the average processed bulk diffusion lengths can be consistently made to be of the order of the material thickness, and schemes implemented for utilizing back-surface fields and reducing emitter recombination. The options for achieving these conditions expand and chances of success will be improved with the achievement of growth of 200-micron-thick EFG sheet that is the target of current research and development programs at Mobil Solar. Factors influencing material lifetime improvements and the potential for making greater than 14%-efficient solar cells as EFG material thickness decreases will be examined.

**PHOTOVOLTAIC-RELEVANT PROPERTIES OF INTRINSIC POINT DEFECTS IN
CRYSTALLINE SILICON**

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Intrinsic point defects such as vacancies and self-interstitials are involved in precipitation processes of oxygen and carbon, agglomeration of intrinsic point defects ("swirls") dislocation climb, and gettering processes. All these processes, in turn, may influence the minority carrier lifetime and therefore the efficiency of solar cells based on single or polycrystalline silicon. The paper will review what is presently known about the properties of vacancies and self-interstitials such as their thermal equilibrium concentrations and diffusivities. We will also report on recent measurements of grown-in vacancy concentrations by a method using platinum decoration of vacancies.

SIMS ANALYSIS OF CHROMIUM GETTERING IN CRYSTALLINE SILICON

S.E. Asher

National Renewable Energy Laboratory

J.P. Kalejs and B. Bathey

Mobil Solar Energy Corporation

Secondary ion mass spectrometry (SIMS) is an established technique for the determination of trace-level impurities and dopants in semiconductor materials. In this work SIMS is used to study the gettering of chromium from silicon into the phosphosilicate glass layer which is formed during the processing of photovoltaic devices. Low-dose ion implants are used to introduce chromium into the silicon lattice. Depth profiles from the as-implanted and the phosphorus diffused materials show that the majority of chromium is removed from the silicon during the diffusion of phosphorus to form the p-n junction.

**ROLE OF IMPURITIES AND DEFECTS IN POLYCRYSTALLINE
SILICON SOLAR CELLS**

A. Rohatgi, P. Sana, Z. Chen, J. Salami,
M.S. Ramanachalam, and W.B. Carter
Georgia Institute of Technology

In spite of recent accomplishments in polycrystalline cell efficiency, exact identification and the role of efficiency-limiting defects and mechanisms in polycrystalline cells is not fully understood. The object of this research is to provide guidelines for achieving high cell efficiencies on polycrystalline silicon through fundamental understanding of gettering and light-induced effects. Theoretical modeling was performed to quantify the effects of illumination level on polycrystalline silicon cells. It was found that grain boundary barrier height decreases and the diffusion length increases with the illumination level. The enhanced diffusion length effect was also found to be more pronounced in smaller grain materials. Attempts were made to achieve high-efficiency polycrystalline by a combination of gettering and passivation. Phosphorus diffusion on the front and Aluminum treatment at the back were used for gettering that resulted in 17.7% efficient solar cells on Osaka Titanium polycrystalline silicon.

RECOMBINATION AT CLEAN AND DECORATED MISFIT DISLOCATIONS

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The electrical activity of interfacial misfit dislocations in silicon has been examined using the electron beam induced current technique in a scanning electron microscope. Clean dislocations formed during high-temperature Si(Ge) chemical vapor epitaxy were studied. These defects were subsequently decorated with known metallic impurities (Au and Ni) by diffusion at different temperatures. Two sources of metallic impurities were used: back-side evaporated layer, as a infinite source, and ion implantation as a finite one. Differences in electrical activity are discussed in relation to the level of decoration, energy levels anticipated for the clean or decorated dislocations, and detection limits of electron beam induced current technique.

**PHOTOLUMINESCENCE AND ELECTROLUMINESCENCE PROPERTIES OF
POROUS SILICON**

M.J. Heben, Y. Xiao, J. McCullough, Y.S. Tsuo, J.I. Pankove,
and S.K. Deb

National Renewable Energy Laboratory

A porous silicon (PS) layer can be produced on a crystalline silicon substrate by electrochemical etching in hydrofluoric acid solutions. There are many properties that make PS thin films interesting for photovoltaic applications, such as a possible direct bandgap that can be adjusted between 1.5 and 1.9 eV, textured surfaces for light trapping, potential for low-cost and large-area fabrication, and the possibility of tandem cell structures with Si. Recent experimental efforts at NREL include fabricating large areas (up to 3" diameter) of visibly uniform PS, studies of photoluminescence degradation and posthydrogenation effects, and the fabrication of solid state junctions for studying electroluminescence. We have observed that, for some PS samples, the PL intensity after remote-plasma rehydrogenation can be 25 times greater than that of the as-grown sample.

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SESSION VI

FRIDAY A.M.

**OTHER PHOTOVOLTAIC
AND SAFETY PERSPECTIVES**

PHOTOVOLTAICS IN EUROPE - RECENT DEVELOPMENTS

H.W. Schock and F. Pfisterer

Universität Stuttgart

Institut für Physikalische Elektronik

Recent developments of photovoltaics in Europe are reviewed. The status of cell technology will be summarized. Special attention will be directed to achievements in polycrystalline thin-film solar cell technology.

Aspects of systems and implementation of photovoltaics on various levels are discussed in view of specific conditions in Europe.

THE PHOTOVOLTAICS PROGRAM AT SANDIA NATIONAL LABORATORIES*

D.E. Hasti

Photovoltaic Projects Manager
Sandia National Laboratories

The Sandia Photovoltaics Projects support the DOE Photovoltaics Program goal to establish photovoltaics, produced by U.S. industry, as a significant energy source for domestic and international applications. The realization of that goal requires meeting the following requirements: a cost-effective product which delivers energy or equivalent (or better) quality; an industry capable of sustained investment in continued product evolution; time-phased market development matched to industry capability; and an educated, willing customer operating in an equitable policy environment. How the Sandia PV Projects work with industry to address all of these requirements will be discussed.

*Prepared by Sandia National Laboratories, Albuquerque, NM

**EPRI PHOTOVOLTAICS ACTIVITIES: TECHNOLOGY ADVANCEMENT
AND APPLICATIONS DEVELOPMENT**

E.A. DeMeo

Manager, Solar Power Program

Electric Power Research Institute

The EPRI program in photovoltaics (PV) focuses on two primary thrusts:

- advancement of PV technology toward high-performance, affordable systems for energy-significant electric-utility use
- identification, evaluation, and facilitation of PV applications in the utility sector.

The first thrust includes a coordinated, multi-university effort in amorphous-silicon materials and device research that is transitioning toward enhanced transfer to industry; and a comprehensive industry-based program in high-concentration PV systems development. The second thrust is aimed currently at high-value uses that are cost-effective today and is expanding to the next generation of applications where PV is expected to compete later in this decade.

**AN UPDATE ON ENVIRONMENTAL, HEALTH, AND SAFETY ISSUES IN THE
PHOTOVOLTAIC INDUSTRY**

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Biomedical and Environmental Assessment Group
Brookhaven National Laboratory

There is growing interest in the environmental, health, and safety implications of new photovoltaic material and process options as they approach commercialization. Several issues of importance include the impacts of new environmental regulations on module manufacturers, potential toxicity of III-V and II-VI compounds, and need for recycling of spent modules and manufacturing wastes. This paper will review these topics. Special attention will be paid to the new Clean Air Act Amendments-Hazardous Air Pollutant Requirements, the newly promulgated OSHA Process Safety standards, an update on the toxicity of CdTe and an overview of emerging studies of CIS and CdTe compounds, and options for the recycling of modules and production wastes.

**AN OVERVIEW OF SAFETY ASSESSMENT, REGULATION AND
CONTROL OF HAZARDOUS MATERIAL USE AT NREL**

B.P. Nelson

National Renewable Energy Laboratory

We have developed a methodology for ensuring the safe use of hazardous materials in our facilities. First, we study federal, state, and local regulations and apply the relevant requirements to our operations. When necessary, we generate internal safety documents to consolidate this information. We design research operations and support systems to conform to these requirements and perform a semi-quantitative risk analysis on likely accident scenarios. All scenarios presenting an unacceptable risk require system or procedural modifications to reduce the risk. Once all risks are acceptable, operations begin only after an operational readiness review by a management-appointed panel.

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